Chapter 6
Structural Evaluation

6-1. Purpose of Evaluation

a. Structural evaluation is the process of determining the capability of a structure to perform its intended function. The evaluation includes the assessment of both the long- and short-term effects of all reported damage and unusual loading conditions. It results in recommendations that include the requirements for future inspections, any repair and maintenance procedures, and the urgency of these tasks. The engineering decision on appropriate repair or planned maintenance is based on the concept of fitness for service of the distressed structure. A structure is fit for service when it functions satisfactorily during its lifetime without reaching any serious limit state.

b. In order to perform a structural evaluation, performance criteria and analytical tools are needed. Loading and performance criteria for hydraulic steel structures are outlined in EM 1110-2-2105, EM 1110-2-2701, EM 1110-2-2702, and EM 1110-2-2703. Basic fatigue and fracture analysis concepts are presented in this chapter and in Chapter 2, and traditional structural analysis techniques can be applied for the assessment of corrosion damage and plastically deformed members. Quantitative techniques for corrosion effects on bridges and sheet piling have been developed based on reliability concepts (Kayser and Nowak 1987, 1989; Mlakar et al. 1989).

6-2. Fracture Behavior of Steel Materials

a. The operating service temperature of a steel structure has a significant effect on the fracture behavior of the steel. For low- and intermediate-strength steels, the material changes from brittle fracture behavior (i.e., critical stress intensity factor K_{Ic} applies when the state of stress at the crack tip is plane strain) to ductile fracture behavior (i.e., critical stress intensity factor K_c or crack-tip opening displacement (CTOD) applies) at a certain transition temperature. This temperature is called the nil-ductility transition (also abbreviated as NDT, which should not be confused with nondestructive testing, also NDT) temperature and is measured by the drop weight test in accordance with ASTM E208. The nil-ductility transition temperature is defined as the highest temperature at which a standard specimen breaks in a brittle manner under dynamic loading. At temperatures above the nil-ductility transition temperature, the material has sufficient ductility to deflect inelastically before total fracture. Below the nil-ductility transition temperature, the fracture toughness remains relatively constant with changing temperature. For impact loading, the nil-ductility transition temperature approximately defines the upper limit of the plane-strain condition as shown in Figure 6-1.

b. For steel, the nil-ductility transition temperature depends on material thickness and applied loading rate. The anticipated level of structural performance (i.e., brittle or ductile) can be determined from the results of the fracture toughness test performed at temperatures around the transition temperature. With an additional consideration of the geometric constraint effect due to material thickness (i.e., β_{Ic} factor, Equation 2-2), the appropriate fracture parameter K_{Ic}, K_c, or CTOD can be selected for fracture analysis. For structures subject to static or dynamic loading, the respective fracture toughness-to-temperature relations must be used to characterize the fracture behavior. Figure 6-1 shows the schematic relationships between level of structural performance and service temperature for various loading rates (Barsom and Rolfe 1987) (see also paragraph 7-1.).

6-3. Fracture Analysis

a. When inspections reveal discontinuities (i.e., cracks or flaws), it is necessary to establish acceptance levels to determine if repairs are needed to prevent fracture. Fracture mechanics may be used to establish acceptance levels for various discontinuities by comparing the discontinuity size with the critical discontinuity

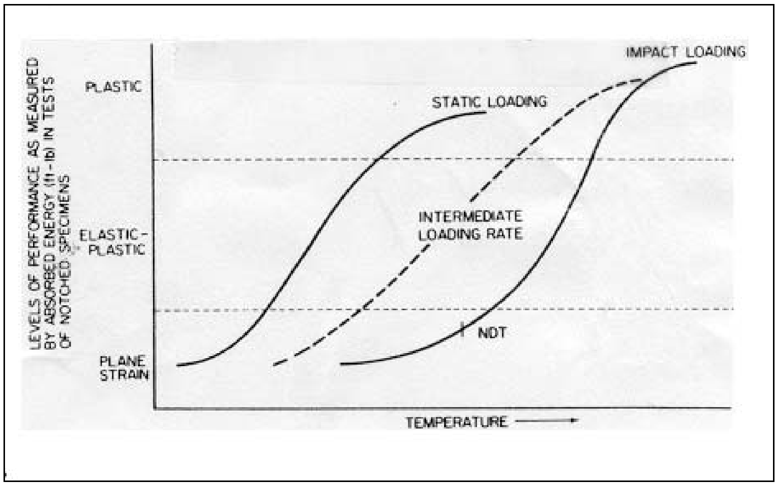


Figure 6-1. Relation between notch toughness and loading rates (Barsom and Rolfe (1987), p 110. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)

size. Each case is unique depending on a given set of loads, environmental factors (e.g., temperature), geometry, and material properties. The critical discontinuity size is determined using fracture mechanics principles, which relate stress, discontinuity size, and fracture toughness to existing conditions. If the discontinuity size is less than the critical size, fracture will not likely occur and the expected remaining life may be determined by a fatigue analysis. To ensure this, the stress-intensity factor K_I must be less than the critical stress-intensity factor K_{Ic}, K_{Id}, or K_c, or CTOD must be less than the critical CTOD value δ_{crit}. K_{Id} is the critical stress-intensity factor for dynamic loading and plane-strain conditions.

b. For hydraulic steel structures operating at a minimum service temperature that is below the nil-ductility transition temperature, linear elastic fracture mechanics (LEFM) analysis is required to assess the discontinuities revealed from inspections. For structures with discontinuities operating at temperatures above the nil-ductility transition temperature, elastic-plastic fracture mechanics (EPFM) analysis needs to be conducted. In any case, LEFM may be used as an initial evaluation tool, since it is simple to apply and generally gives a conservative answer. (In nonlinear elastic cases, LEFM analysis would be applied using K_c as the critical stress intensity factor.) As discussed in Chapter 2, the three key parameters in a fracture analysis are stress level, crack geometry, and the fracture toughness. Reliable estimates of each of these parameters should be determined. The magnitude of stress used in a fracture analysis should be determined from a reasonably detailed analysis. The crack geometry should be accurately measured during the inspection process as discussed in Chapter 4. This includes the size, shape, and orientation of the crack. Determination of material toughness is discussed in Chapters 5 and 7. An example fracture evaluation is also provided in Chapter 7.

c. The procedure of fracture assessment of discontinuities may be described by the following steps. The flow chart is shown in Figure 6-2.

(1) Determine the actual shape, location, and size of the discontinuity by NDT inspection.

(2) Determine the effective discontinuity dimensions to be used for analysis (British Standards Institution 1980; Burdekin et al. 1975; and American Society of Mechanical Engineers (ASME) 1978). Discontinuities are classified as through thickness (may be detected from both surfaces), embedded (not visible from either surface), or surface (may be observed on one surface) as illustrated in Figure 6-3. To determine the effective dimensions of a discontinuity:

(a) Resolve the discontinuity into a plane normal to the principal stresses as shown in Figure 6-4. Effective dimensions for various isolated discontinuity types are shown in Figure 6-3.

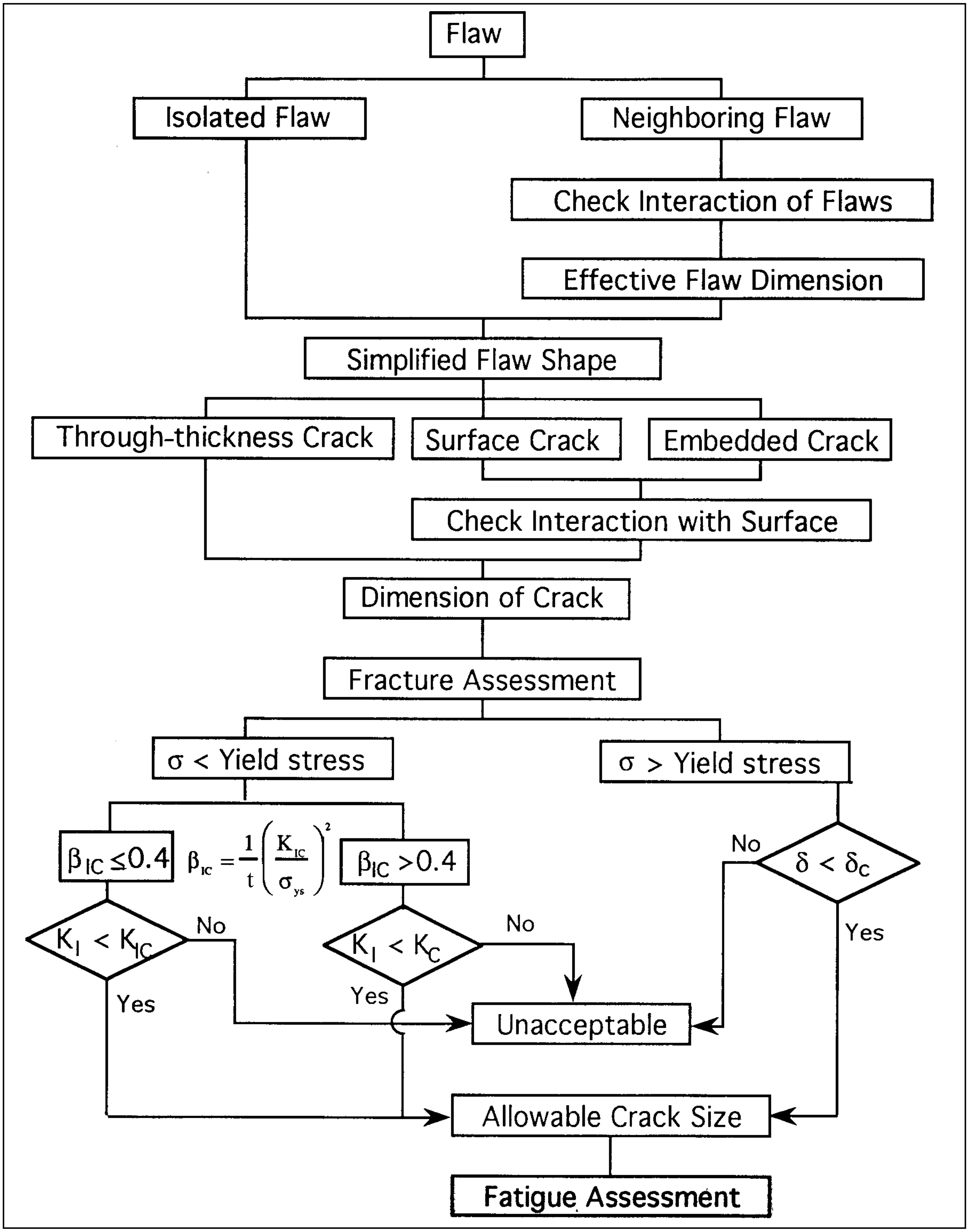


Figure 6-2. Fracture and fatigue assessment procedure where *t* = thickness of component, δ = crack tip opening displacement, δ_c = critical crack tip opening displacement

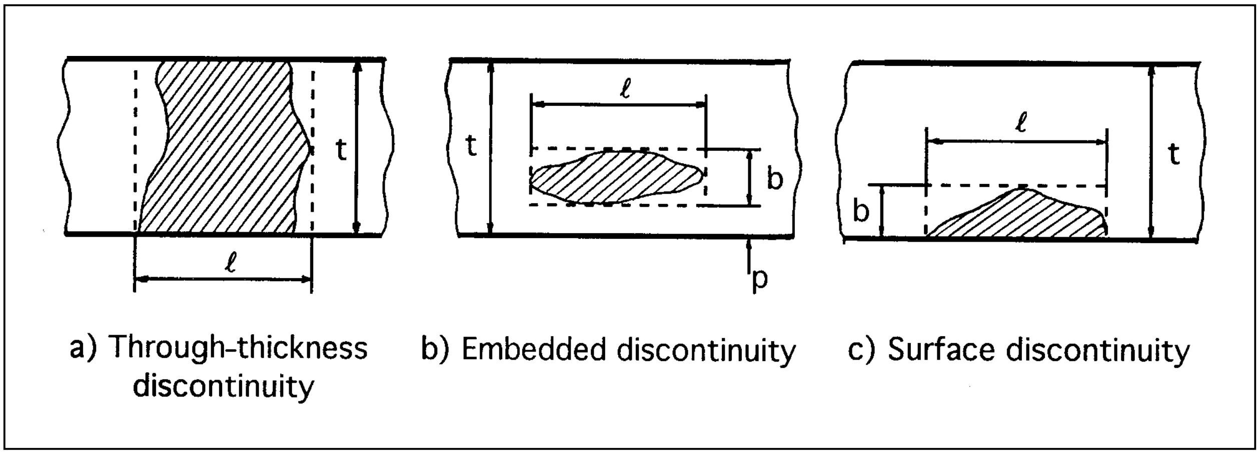


Figure 6-3. Required dimensions of a discontinuity (after British Standards Institution 1980) where *t* = component thickness, *l* = effective crack length, (2a), *b* = effective dimension of crack in the through-thickness direction, and *P* = effective dimension of the distance between the edge of component and edge of crack in the through-thickness direction

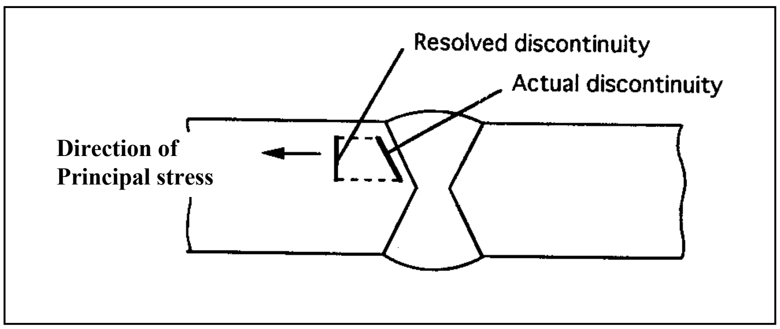


Figure 6-4. Resolution of a discontinuity (after British Standards Institution 1980)

(b) Check interaction with neighboring discontinuities to obtain the idealized discontinuity dimensions; idealizations for interaction of discontinuities are shown in Figures 6-5 and 6-6.

(c) Check interaction with surfaces by recategorization as shown in Figure 6-7 for surface or embedded discontinuities (idealized or actual).

(d) Determine final idealized effective dimensions for fracture analysis.

(3) Determine the stress level by an appropriate structural analysis, assuming no crack exists. Structural loading can be divided into primary stress σ_p and secondary stress σ_s. The primary stress consists of membrane stress σ_m and bending stress σ_b, due to imposed loading. Examples of secondary stresses include stress increase due to stress concentration imposed by geometry of the detail under consideration, thermal stress, and residual stress. For discontinuities at non-heat-treated welds, the residual tensile stress should be taken as the yield stress. An estimate of the residual stress should be used for post-heat-treated weldments. The applied stress is the sum of primary σ_p and secondary σ_s stresses. If the applied stress is greater than the yield stress, EPFM must be employed. If applied stress is less than the yield stress and the plane-strain factor $\beta_{Ic} \leq 0.4$ (Equation 2-2), LEFM should be used based on K_{Ic}. When the applied stress is less than the yield stress and $\beta_{Ic} > 0.4$, K_c (a function of plate thickness) should be used instead of K_{Ic}, if available. Otherwise, EPFM based on CTOD analysis must be employed.

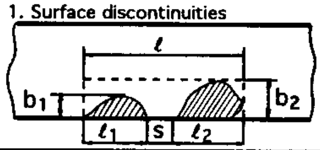
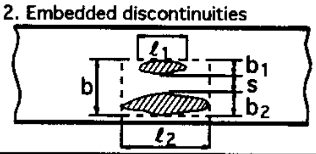
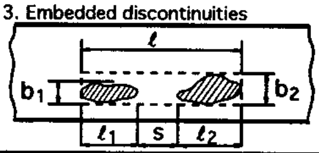
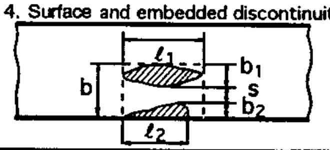
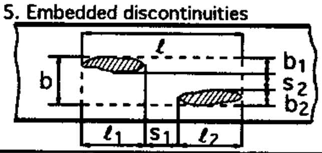
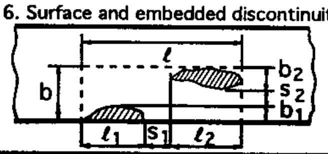
Discontinuities	Criterion for interaction	Effective dimensions after interaction
1. Surface discontinuities 	$s < \frac{\ell_1 + \ell_2}{2}$	$b = b_2$ $\ell = \ell_1 + \ell_2 + s$
2. Embedded discontinuities 	$s < \frac{b_1 + b_2}{2}$	$b = b_1 + b_2 + s$ $\ell = \ell_2$
3. Embedded discontinuities 	$s < \frac{\ell_1 + \ell_2}{2}$	$b = b_2$ $\ell = \ell_1 + \ell_2 + s$
4. Surface and embedded discontinuities 	$s < \frac{b_1}{2} + b_2$	$b = b_1 + b_2 + s$ $\ell = \ell_1$
5. Embedded discontinuities 	$s_1 < \frac{\ell_1 + \ell_2}{2}$ and $s_2 < \frac{b_1 + b_2}{2}$	$b = b_1 + b_2 + s_2$ $\ell = \ell_1 + \ell_2 + s_1$
6. Surface and embedded discontinuities 	$s_1 < \frac{\ell_1 + \ell_2}{2}$ and $s_2 < b_1 + \frac{b_2}{2}$	$b = b_1 + b_2 + s_2$ $\ell = \ell_1 + \ell_2 + s_1$

Figure 6-5. Interaction of coplanar discontinuities (Extracts from British Standards Institution 1980. Complete copies of the standard can be obtained by post from BSI Publications, Linford Wood, Milton Keynes, MK14 6LE)

(4) Determine material properties including yield strength σ_{ys}, modulus of elasticity E, K_{Ic} (based on the level of applied stress and the value of β_{Ic}), K_c, or CTOD. K_{Ic} may be estimated from Charpy V-Notch (CVN) test values by the transition method (paragraph 5-8) if direct K_{Ic} test data are not available.

(5) Perform fracture assessment to determine the critical discontinuity size.

(6) If the discontinuity is noncritical, determine the remaining life using a fatigue analysis as described in paragraphs 6-7 and 6-8.

These steps are further discussed in the following paragraphs.

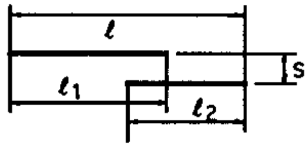
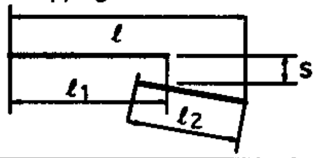
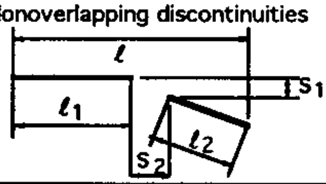
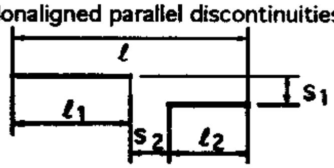
Discontinuities	Criterion for interaction	Effective dimensions after interaction
1. Overlapping parallel discontinuities 	$s < \frac{\ell_1 + \ell_2}{2}$	Length = ℓ
2. Overlapping discontinuities 	$s < \frac{\ell_1 + \ell_2}{2}$	Length = ℓ
3. Nonoverlapping discontinuities 	$s_1 < \frac{\ell_1 + \ell_2}{2}$ and $s_2 < \frac{\ell_1 + \ell_2}{2}$	Length = ℓ
4. Nonaligned parallel discontinuities 	$s_1 < \frac{\ell_1 + \ell_2}{2}$ and $s_2 < \frac{\ell_1 + \ell_2}{2}$	Length = ℓ

Figure 6-6. Interaction of noncoplanar discontinuities (Extracts from British Standards Institution 1980. Complete copies of the standard can be obtained by post from BSI Publications, Linford Wood, Milton Keynes, MK14 6LE)

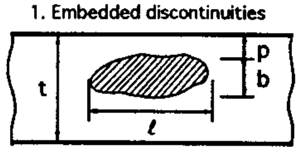
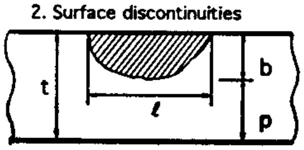
Discontinuities	Criterion for interaction	Effective dimensions after interaction
1. Embedded discontinuities 	$\frac{p}{b} < 0.5$	Length = ℓ Height = b + p
2. Surface discontinuities 	$\frac{b}{t} > 0.5$	Through thickness crack : length = ℓ

Figure 6-7. Interaction of discontinuities with surfaces (Extracts from British Standards Institution 1980. Complete copies of the standard can be obtained by post from BSI Publications, Linford Wood, Milton Keynes, MK14 6LE)

6-4. Linear-Elastic Fracture Mechanics

a. Fundamental concepts of LEFM are described by Barsom and Rolfe (1987). LEFM is valid only under plane-strain conditions, when $\beta_{Ic} \leq 0.4$. The basic principle of LEFM is that incipient crack growth will occur when the stress-intensity factor K_I (the driving force) equals or exceeds the critical stress-intensity factor K_{Ic} (or K_{Id} for dynamic loading) (the resistance). For nonplane-strain cases, an initial evaluation based on an approximate analysis using LEFM with K_c taken as the resistance could be carried out.

b. K_I characterizes the stress field in front of the crack and is related to the nominal stress σ and crack dimension a for a given load rate and temperature by

$$K_I = C\sigma\sqrt{a} \tag{6-1}$$

where C is the dimensionless correction factor for a given geometry and loading type. If C is known, K_I can be computed for any combination of σ and a. Stress-intensity factors for various types of geometries can be calculated using the information included in Figures 6-8 through 6-16 (Barsom and Rolfe 1987). Barsom and Rolfe and Tada, Paris, and Irwin (1985) contain compilations of solutions for a wide variety of configurations.

c. After the stress-intensity factor is determined by Equation 6-1, it should be compared to the critical stress-intensity factor K_{Ic} (or K_{Id} for dynamic loading, or K_c for approximated nonplane-strain cases). A factor of safety (FS) = 2.0 applied to crack length is considered appropriate to prevent fracture. Therefore, the crack is considered to be acceptable if $K_I < K_{ic} / \sqrt{2}$.

d. To determine the allowable maximum crack size or nominal stress for a given K_{Ic} (or K_{Id} or K_c), substitute K_{Ic} for K_I and solve for a or σ using Equation 6-1. The critical discontinuity size a_{cr} a structural member can tolerate at a given nominal stress σ and K_{Ic} with a factor of safety applied to the crack size is given by Equation 6-2:

$$a_{cr} = \frac{1}{FS}\left(\frac{K_{Ic}}{C\sigma}\right)^2 \tag{6-2}$$

e. In determining the nominal stress when stress gradients are present, an approximate method is to linearize the stress distribution, and divide it into membrane stress σ_m and bending stress σ_b. The stress-intensity factor for each component of stress can be calculated separately and then added together. The total applied stress (σ_p and σ_s) can be linearized and resolved into σ_m and σ_b as shown in Figure 6-17.

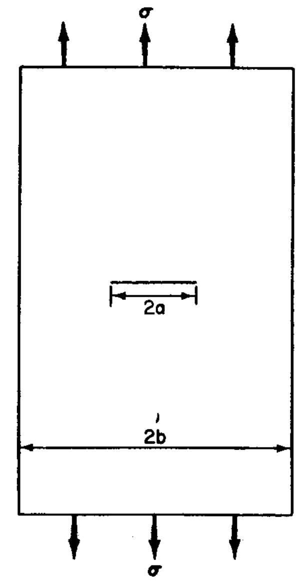
6-5. Elastic-Plastic Fracture Assessment

Rearranging Equation 2-2, the upper limit of plane-strain behavior may be determined as

$$\frac{K_{Ic}}{\sigma_{ys}} = \sqrt{\frac{t}{2.5}} \tag{6-3}$$

When this upper limit is exceeded, extensive plastic deformation occurs at the crack tip (crack tip blunting) and a nonlinear EPFM model must be used for analysis. (LEFM analysis using K_c may be used if the applied stress is less than yield stress.) Crack growth criteria for nonlinear fractures can be modeled by an R-curve, J-integral, or CTOD analysis (Barsom and Rolfe 1987). The CTOD method is the recommended method of EPFM analysis for evaluating hydraulic steel structures. The recommended procedure for cases where the applied stress ($\sigma_p + \sigma_s$) is greater than the yield stress is as follows (British Standards Institution 1980).

$$K_I = \sigma\sqrt{\pi a}\left(\frac{2b}{\pi a}\tan\frac{\pi a}{2b}\right)^{1/2}$$



a/b	$[2b/\pi a \cdot \tan \pi a/2b]^{1/2}$
0.074	1.00
0.207	1.02
0.275	1.03
0.337	1.05
0.410	1.08
0.466	1.11
0.535	1.15
0.592	1.20

Figure 6-8. Through-thickness crack (Barsom and Rolfe 1987, p 39. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)

$$K_I = 1.12\sigma\sqrt{\pi a}\left(\frac{2b}{\pi a}\tan\frac{\pi a}{2b}\right)^{1/2}$$

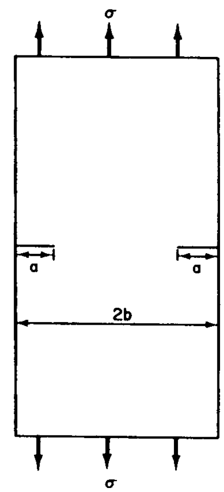


Figure 6-9. Double-edge crack (Barsom and Rolfe 1987, p 40. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)

a. Determine the effective discontinuity parameter $\bar{a}$. This is the equivalent through-thickness dimension that would yield the same stress intensity as the actual discontinuities under the same load.

(1) For through-thickness discontinuities, $\bar{a} = \ell/2$, where ℓ is the measured crack length.

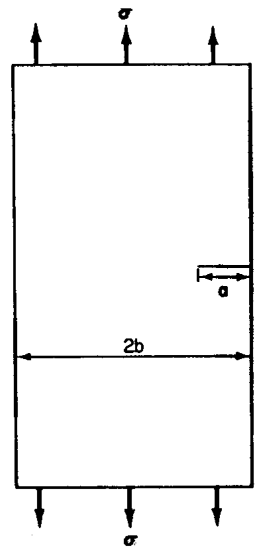
(2) For surface discontinuities, $\bar{a}$ is determined by Figure 6-18.

(3) For embedded discontinuities, $\bar{a}$ is determined by Figure 6-19.

b. Determine allowable discontinuity parameter $\bar{a}_m$ that is calculated by

$$\bar{a}_m = C\left[\frac{\delta_{crit}}{\varepsilon_y}\right] \qquad (6\text{-}4)$$

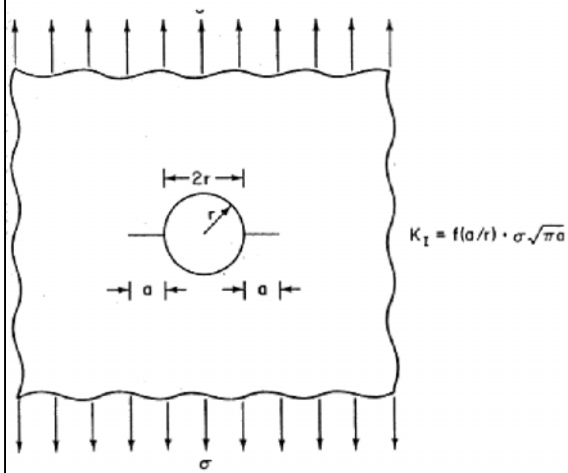
$$K_I = 1.12\,\sigma\sqrt{\pi a} \cdot k\left(\frac{a}{b}\right)$$



a/b	$k(a/b)$
0.10	1.03
0.20	1.07
0.30	1.15
0.40	1.22
0.50	1.35
0.60	1.50
0.70	1.69
0.80	1.91
0.90	2.20
1.00	2.55

Figure 6-10. Single-edge crack (Barsom and Rolfe 1987, p 40. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)

$$K_I = \sigma\sqrt{\pi a} \cdot f\left(\frac{a}{r}\right)$$



a/r	f(a/r), ONE CRACK	f(a/r), TWO CRACKS
0.00	3.39	3.39
0.10	2.73	2.73
0.20	2.30	2.41
0.30	2.04	2.15
0.40	1.86	1.96
0.50	1.73	1.83
0.60	1.64	1.71
0.80	1.47	1.58
1.0	1.37	1.45
1.5	1.18	1.29
2.0	1.06	1.21
3.0	0.94	1.14
5.0	0.81	1.07
10.0	0.75	1.03
∞	0.707	1.00

Figure 6-11. Cracks growing from round holes (Barsom and Rolfe 1987, p 42. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)

where

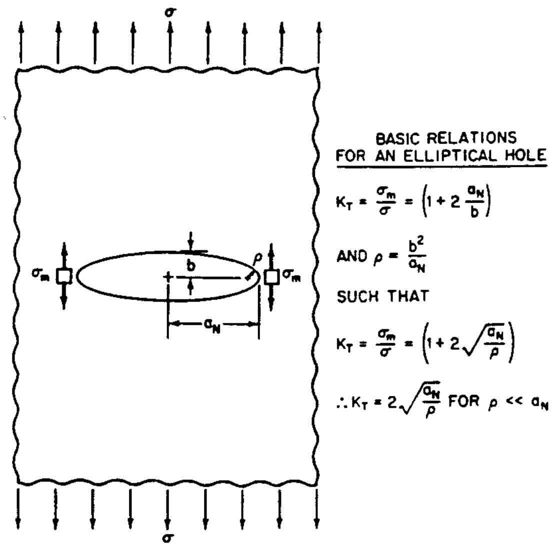
C = values determined by Figure 6-20

δ_{crit} = critical CTOD (paragraph 5-8*c*)

ε_y = yield strain of the material

In determination of C, if the sum of primary and secondary stresses, excluding residual stress, is less than $2\sigma_{ys}$, the total stress ratio $(\sigma_p + \sigma_s)/\sigma_{ys}$ (including residual stress) is used as the abscissa in Figure 6-20. If this sum exceeds $2\sigma_{ys}$, an elastic-plastic stress analysis should be carried out to determine the maximum equivalent plastic strain that would occur in the region containing the discontinuity if the discontinuity were not present. The value of C may then be determined using the strain ratio $\varepsilon/\varepsilon_y$ as the abscissa in Figure 6-20.

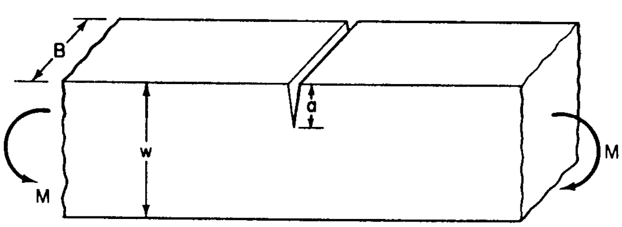
$$K_I = K_T \cdot \sigma\sqrt{\pi \Delta a_F}$$



where $K_T = 2\sqrt{a_N/\rho}$ for $\rho << a_N$ and Δa_F
is the length of the short crack
that is growing from the tip of the ellipse

Figure 6-12. Cracks growing from elliptical holes (Barsom and Rolfe 1987, p 43. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ) where K_T = theoretical stress concentration factor, a_N = half of the long dimension of the ellipse, b = half of the short dimension of the ellipse, and f = radius at the narrow end of the ellipse

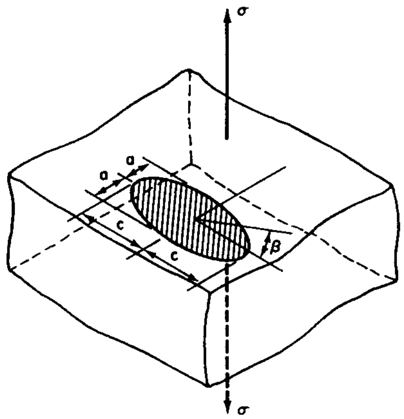
$$K_I = \frac{6M}{B(W-a)^{3/2}} \cdot g\left(\frac{a}{W}\right)$$



a/W	0.05	0.1	0.2	0.3	0.4	0.5	0.6 (and larger)
$g(a/W)$	0.36	0.49	0.60	0.66	0.69	0.72	0.73

Figure 6-13. Edge-notched beam in bending (Barsom and Rolfe 1987, p 45. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ) where M = bending moment per unit thickness, B = beam width, W = beam depth, and g = function that describes effect of a/w on K_I

$$K_I = \frac{\sigma\sqrt{\pi a}}{\Phi_0}\left(\sin^2\beta + \frac{a^2}{c^2}\cos^2\beta\right)^{1/4}$$

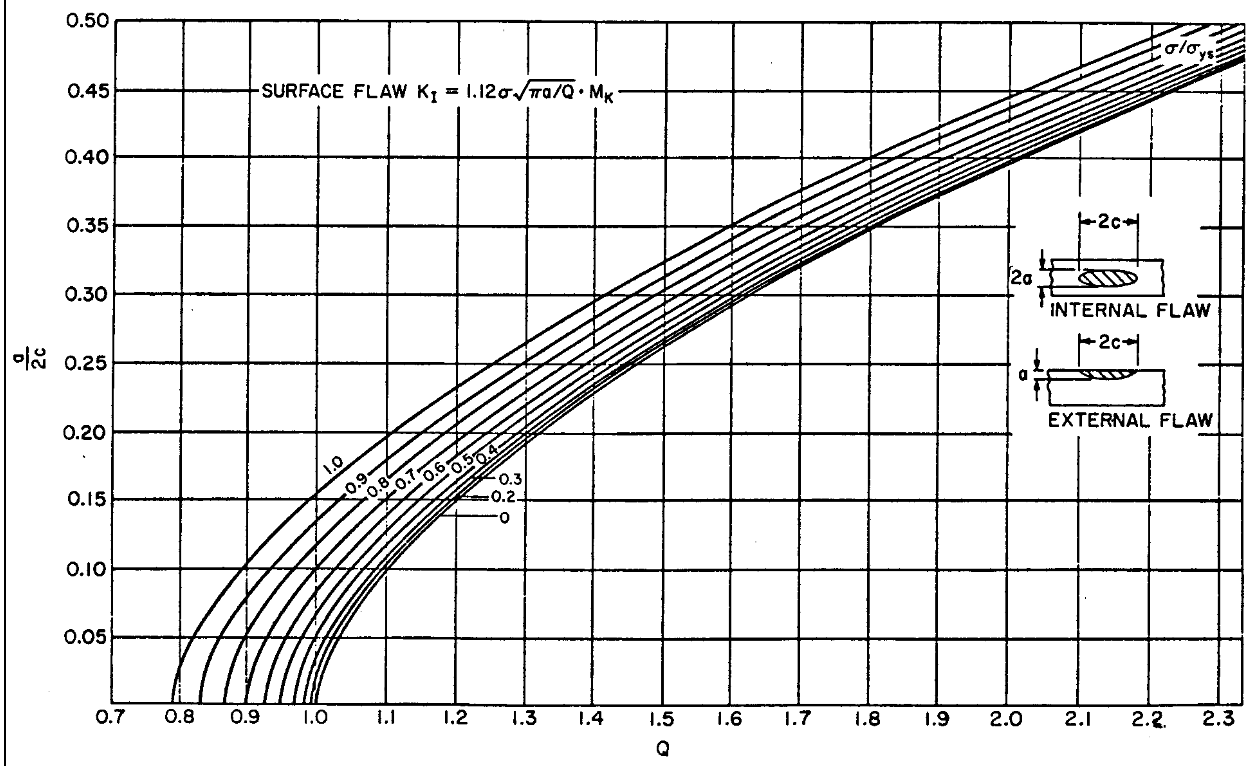


Φ_0 is the elliptic integral

$$\Phi_0 = \int_0^{\pi/2}\left[1 - \left(\frac{c^2 - a^2}{c^2}\right)\sin^2\theta\right]^{1/2} d\theta$$

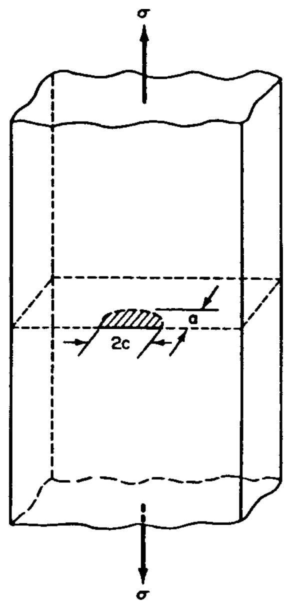
The stress-intensity factor for an embedded elliptical crack reaches a maximum at $\beta = \pi/2$ and is given by the equation

$$K_I = \sigma\sqrt{\pi\frac{a}{Q}} \qquad \text{where } Q = \Phi_0^2$$



Effect of $a/2c$ ratio and σ/σ_{ys} ratio on flaw-shape parameter Q.

Figure 6-14. Embedded elliptical or circular crack (Barsom and Rolfe 1987, p 47. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)



$$K_I = 1.12\,\frac{\sigma\sqrt{\pi a}}{\Phi_0}\left(\sin^2\beta + \frac{a^2}{c^2}\cos^2\beta\right)^{1/4}$$

Φ_0 is the elliptic integral

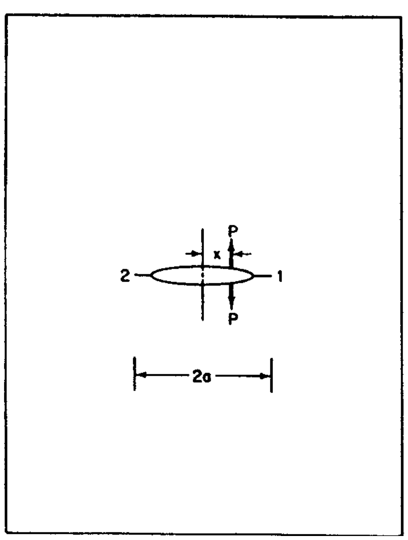
$$\Phi_0 = \int_0^{\pi/2}\left[1 - \left(\frac{c^2 - a^2}{c^2}\right)\sin^2\theta\right]^{1/2} d\theta$$

The stress-intensity factor for $\beta = \pi/2$ (which is the location of maximum stress intensity) is given by

$$K_I = 1.12\sigma\sqrt{\pi\frac{a}{Q}}\cdot M_K \qquad M_K = 1.0 + 1.2\left(\frac{a}{t} - 0.5\right) \qquad M_K = 1.0 \text{ if } a/t < 0.5$$

where $Q = \Phi_0^2$ and is presented graphically in Figure 6.14.

Figure 6-15. Surface crack (Barsom and Rolfe 1987, p 48. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)



The stress-intensity factor for a crack that is subjected to eccentric line forces, P, per unit thickness, on its surfaces is given by

$$K_{I@1} = \frac{P}{\sqrt{\pi a}}\left(\frac{a + x}{a - x}\right)^{1/2}$$

$$K_{I@2} = \frac{P}{\sqrt{\pi a}}\left(\frac{a - x}{a + x}\right)^{1/2}$$

For centrally applied point forces, namely, $x = 0$,

$$K_{I@1} = K_{I@2} = \frac{P}{\sqrt{\pi a}}$$

Figure 6-16. Cracks with wedge forces (Barsom and Rolfe 1987, p 52. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)

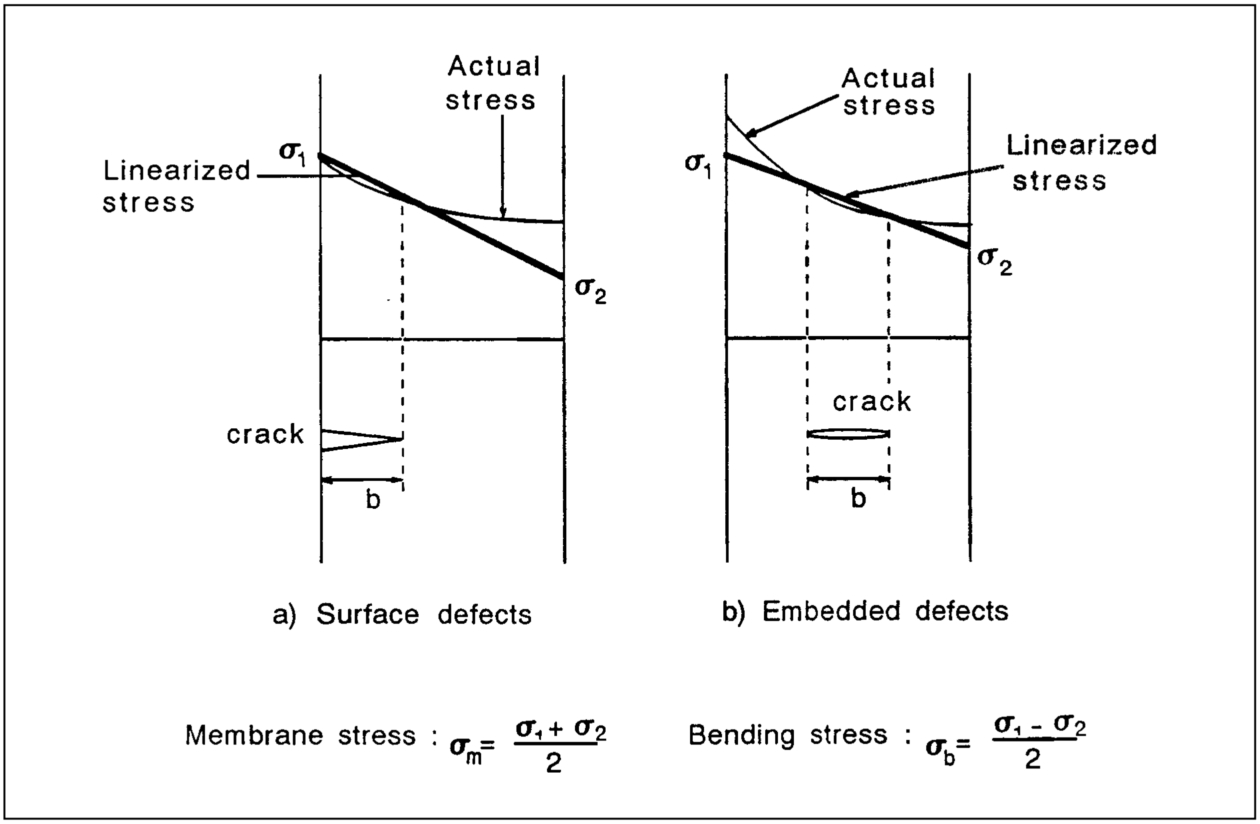


Figure 6-17. Linearization of stresses (Extracts from British Standards Institution 1980. Complete copies of the standard can be obtained by post from BSI Publications, Linford Wood, Milton Keynes, MK14 6LE)

c. If the effective discontinuity parameter $\bar{a}$ is smaller than the allowable discontinuity parameter $\bar{a}_m$, then the discontinuity is acceptable. Using the procedure described in *b* above results in a factor of safety equal to approximately 2.0 in the determination of $\bar{a}_m$; Figure 6-20 was developed as a design curve. Therefore, the calculated critical crack size would be equal to 2.0 $\bar{a}_m$ (British Standards Institution 1980).

6-6. Fatigue Analysis

a. For most lock gates and spillway gates that have vibration problems, fatigue loading is a real concern and a fatigue evaluation may be required. Fatigue analysis is used to predict when the cyclic loading will cause a crack to propagate to critical size resulting in fracture. A fatigue analysis can also provide crack growth rates that are useful in determining inspection intervals.

b. The total fatigue life is the sum of the fatigue crack-initiation life and the fatigue crack-propagation life to a critical size (Barsom and Rolfe 1987).

$$N_T = N_i + N_p \tag{6-5}$$

where

N_T = total fatigue life

N_I = initiation life

N_p = propagation life

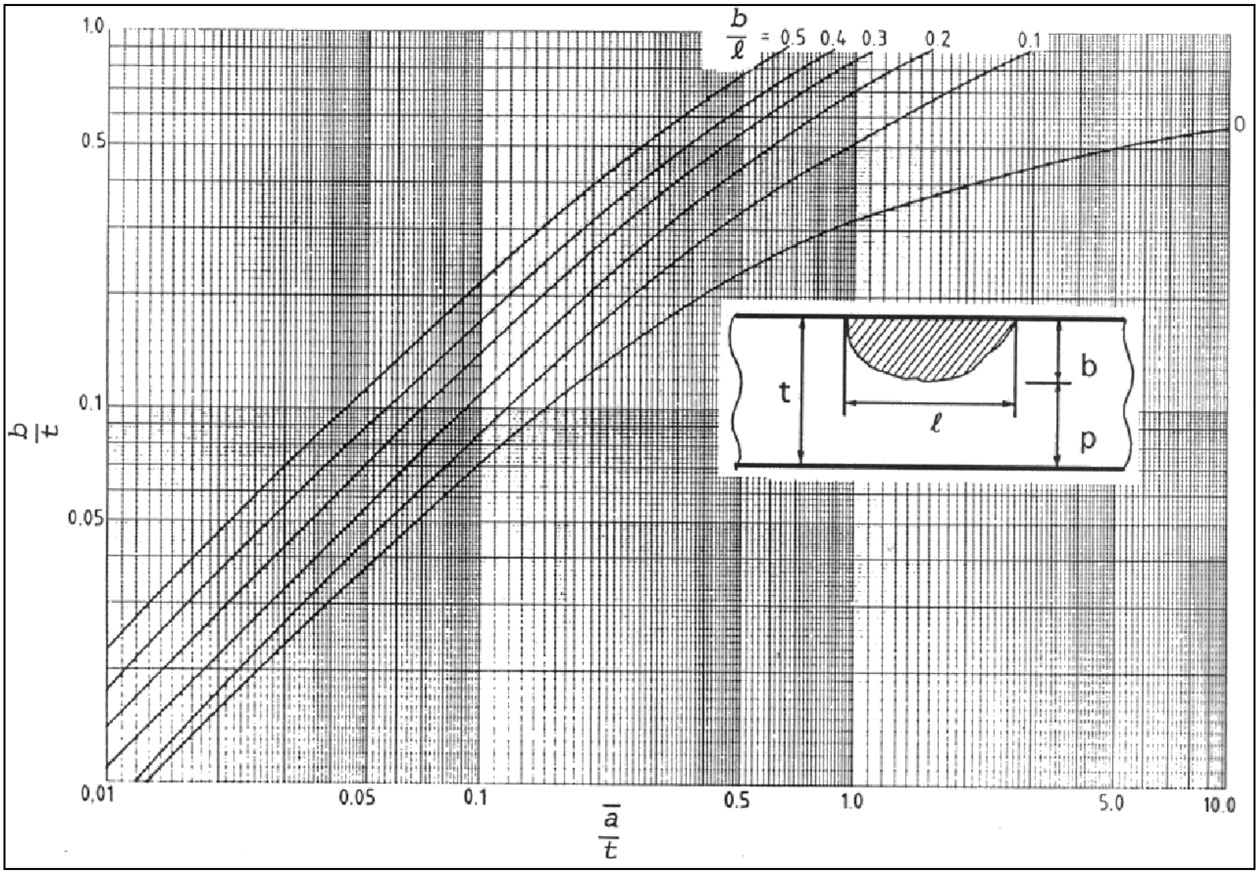


Figure 6-18. Relation between dimensions of a discontinuity and the parameter ā for surface discontinuities. (Extracts from British Standards Institution 1980. Complete copies of the standard can be obtained by post from BSI Publications, Linford Wood, Milton Keynes, MK14 6LE)

c. All steels have microscopic discontinuities, and welded structures always contain larger discontinuities due to the welding process. Thus, the main concern in fatigue assessment of welded structures is to determine the crack-propagation life before the critical crack size is reached that results in brittle fracture. The life of a structural component that contains a crack is governed by the rate of subcritical crack propagation.

d. Fatigue analysis methods described in paragraphs 6-7 and 6-8 are based on extensive analyses of test results from numerous specimens. Variation in test data is large, and inherent uncertainty exists in defining load and strength parameters. Therefore, fatigue life predictions should be used as a means to evaluate a reliable service life, not to actually predict when a structure will fail. Fatigue analysis is needed when the remaining structure life and the crack growth rate are necessary for developing the inspection and maintenance scheduling for a distressed structure as discussed in paragraph 6-11. An example of the estimation of fatigue life from S_r-N curves for a gate with a vibration problem is given in Chapter 7.

6-7. Fatigue Crack-Propagation

The fatigue crack-propagation behavior for metals is shown in Figure 6-21. Figure 6-21 is a plot ($\log_{10}$ scale) of the rate of fatigue crack growth per cycle of load da/dN versus the variation of the stress-intensity factor ΔK_I. The parameter a denotes crack length, N the number of cycles, and ΔK_I the stress-intensity factor range, $K_{I\max}$ to $K_{I\min}$. Based on Figure 6-21, fatigue-crack behavior for steel can be characterized by three regions. Barsom and Rolfe (1987) describe these regions in more detail.

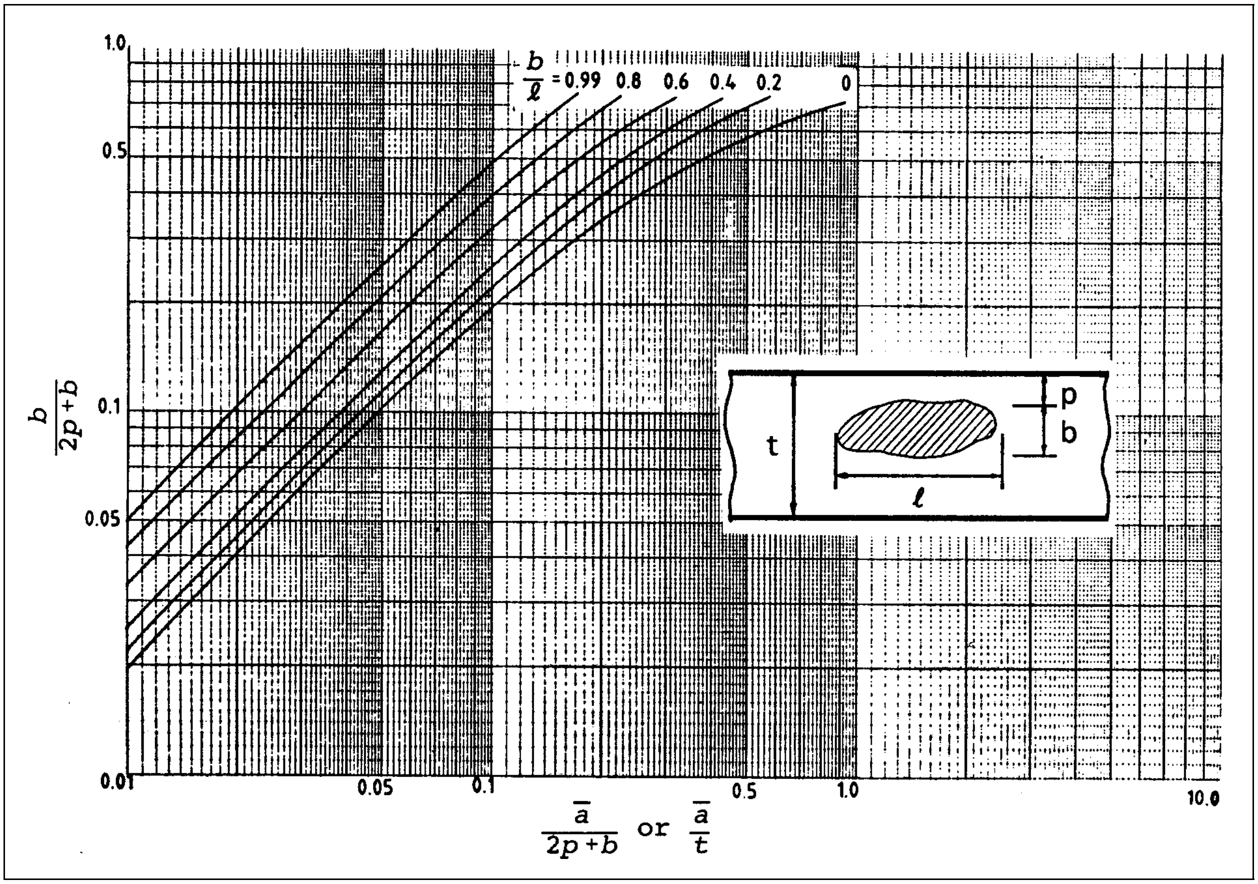


Figure 6-19. Relation between dimensions of a discontinuity and the parameter ā for embedded discontinuities (Extracts from British Standards Institution 1980. Complete copies of the standard can be obtained by post from BSI Publications, Linford Wood, Milton Keynes, MK14 6LE)

a. Region I. In Region I, for levels of ΔK_I below a certain threshold, cracks do not propagate under cyclic stress fluctuations. Conservative estimates of fatigue threshold, ΔK_{th}, can be determined by

$$\Delta K_{th} = 7\ (1 - 0.85R)\ \text{MPa-}\sqrt{\text{m}}\ \ (6.4\ (1 - 0.85R)\ \text{ksi-}\sqrt{\text{in.}}\ )\ \text{ for } R > 0.1$$
$$\Delta K_{th} = 6\ \text{MPa-}\sqrt{\text{m}}\ \ (5.5\ \text{ksi-}\sqrt{\text{in.}}\ )\ \text{for } R < 0.1 \qquad (6\text{-}6)$$

where R is the stress ratio (i.e., fatigue ratio) expressed as

$$R = \sigma_{min} / \sigma_{max} \qquad (6\text{-}7)$$

Residual stress should be considered for a crack near a weld area. If ΔK_I is less than ΔK_{th}, cracks do not propagate.

b. Region II. The fatigue crack-propagation behavior for $\Delta K_I > \Delta K_{th}$ in Region II (i.e., linear portion of the plot in Figure 6-21) may be represented by Equations 6-8 and 6-9. These equations were based on analyses in air at room temperature. Extensive fatigue-crack growth rate data for weld metals and heat-affected zones show that the fatigue rate in weld metals and heat-affected zones is equal to or less than that in the base metals. Thus, Equations 6-8 and 6-9 can also be used for conservative estimates of fatigue-crack growth rates in base metals, weld metals, and heat-affected zones.

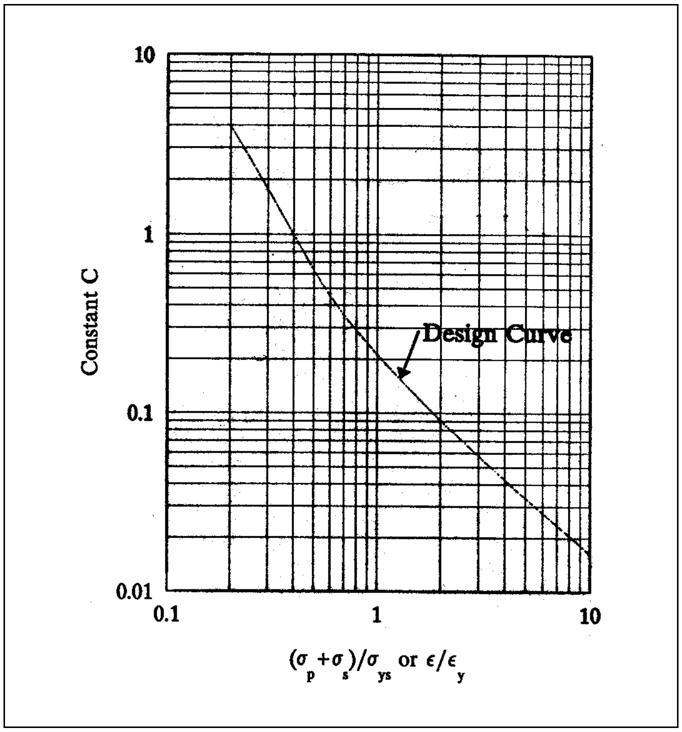


Figure 6-20. Values of constant *C* for different loading conditions (Extracts from British Standards Institution 1980. Complete copies of the standard can be obtained by post from BSI Publications, Linford Wood, Milton Keynes, MK14 6LE)

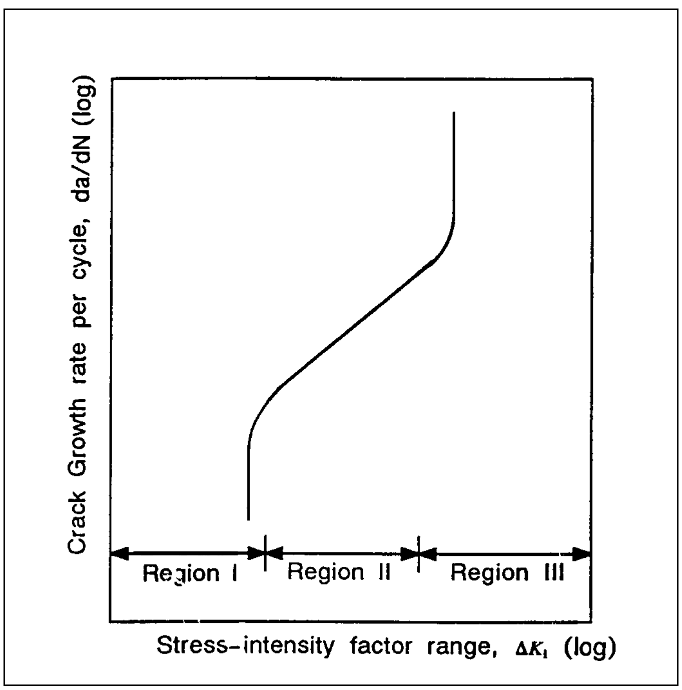


Figure 6-21. Fatigue-crack growth in steel

(1) Ferrite-pearlite steels. ASTM A36M-97 and ASTM A572/572M Grade 50 steels are classified as ferrite-pearlite steels:

$$da/dN = 6.9 \times 10^{-9}\, (\Delta K_I)^3 \tag{6-8}$$

where

a = mm
ΔK_I = MPa-$\sqrt{\text{m}}$

(For non-SI units, $da/dN = 3.6 \times 10^{-10}\, (\Delta K_I)^3$ where a = in. and ΔK_I = ksi-$\sqrt{\text{in.}}$)

(2) Martensitic steels. ASTM A514/A514M and ASTM A517/517M steels are martensitic steels:

$$da/dN = 1.35 \times 10^{-7}\, (\Delta K_I)^{2.25} \tag{6-9}$$

where

a = mm
ΔK_I = MPa-$\sqrt{\text{m}}$

(For non-SI units, $da/dN = 0.66 \times 10^{-8}\, (\Delta K_I)^{2.25}$ where a = in. and ΔK_I = ksi-$\sqrt{\text{in.}}$)

c. Region III. Region III is characterized by a significant increase in the fatigue-crack growth rate per cycle over that predicted for Region II. At a certain value of ΔK_I, the crack growth rate accelerates dramatically. For materials of high fracture toughness, the stress-intensity factor range value corresponding to acceleration in the fatigue-crack growth rate (i.e., transition from Region II to Region III) for zero to tension loading can be determined by Equation 6-10:

$$K_T = 0.0063\, (E\, \sigma_{ys})^{1/2} \tag{6-10}$$

where

K_T = MPa-$\sqrt{\text{m}}$
E, σ_{ys} = MPa

(For non-SI units, $K_T = 0.04\, (E\, \sigma_{ys})^{1/2}$ where K_T = ksi-$\sqrt{\text{in.}}$, and E and σ_{ys} = ksi.)

When the K_{Ic} of the material is less than K_T, acceleration in the fatigue rate occurs at a stress-intensity factor value slightly below K_{Ic}. Due to the acceleration in crack growth rate, a significant increase in fracture toughness of a steel above K_T may have a negligible effect on total fatigue life. Additionally, extrapolation of Region II behavior to Region III may overestimate the total fatigue life significantly.

6-8. Fatigue Assessment Procedures

a. Region II fatigue analysis with known discontinuities. The procedure to analyze Region II crack growth behavior in steels and weld metals using fracture mechanics concepts as recommended by Barsom and Rolfe (1987) is as follows.

(1) On the basis of the inspection data, determine the maximum initial discontinuity size a_o present in the member being analyzed and the associated K_I.

(2) Knowing K_{Ic} and the nominal maximum design stress, calculate the critical discontinuity size a_{cr} (Equation 6-2) that would cause failure by brittle fracture.

(3) Determine fatigue crack growth rate for type of steel (Equations 6-8 and 6-9 for ferrite-pearlite or martensitic steel, respectively).

(4) Determine ΔK_I using the appropriate expression for K_I, the estimated initial discontinuity size a_o, and the range of live load stress S_r (i.e., cyclic stress range). For cases of variable amplitude loading, an equivalent constant amplitude stress range, S_{re} should be computed as described in paragraph 2-3*e*. A live load stress range S_r, which is due to cyclic compression stresses, may be detrimental in regions where tensile residual stress exists. In these regions, cracks may propagate, since the addition of tensile residual stresses will result in an applied stress range of tension and compression. The stress range, S_r, used to determine fatigue life should be calculated from the algebraic difference of the maximum and minimum stresses even when the minimum stress is compression and has a negative value, since any tensile residual stresses will be superimposed on the applied cyclic stress (American Association of State Highway and Transportation Officials 1996; American Institute of Steel Construction 1994; EM 1110-2-2105).

(5) Integrate the crack growth rate expression (i.e., Equations 6-8 and 6-9) between the limits of a_o (at the initial K_I) and a_{cr} (at K_{Ic}) to obtain the life of the structure prior to failure. To identify inspection intervals, integration may be applied with the upper limit being tolerable discontinuity size a_t. An arbitrary safety factor based on analysis uncertainties may be applied to a_{cr} to obtain a_t (a factor of safety of 2.0 is recommended). Another consideration for specifying a tolerable discontinuity size is crack growth rate. The a_t should be chosen so that da/dN is relatively small and a reasonable length of time remains before the critical size is reached.

(6) For a determination of a_o:

(a) See Figure 6-3a for through-thickness discontinuities.

(b) For embedded discontinuities (Figure 6-3b), assume that the discontinuity grows until it reaches a circular shape ($b = \ell/2$). Subsequently, it grows radially and eventually protrudes through a surface at which time it should be treated as a surface discontinuity of length ℓ.

(c) See Figure 6-3c for surface discontinuities. Initial propagation will result in a semicircular shape. Further propagation will result in the discontinuity reaching the other surface at which time it should be treated as a through-thickness discontinuity.

b. Fatigue strength evaluation without known discontinuities.

(1) Welded details. The fatigue life of welded details that do not include known discontinuities shall be determined as described in Chapters 2 and 3.

(2) Riveted details. The following fatigue strength criteria for undamaged and noncorroded riveted details are recommended:

(a) When $S_{rm} \leq 41.4$ MPa (6 ksi), where S_{rm} is the maximum stress range, the possibility of fatigue damage can be ignored.

(b) When S_{re} < 68.9 MPa (10 ksi), where S_{re} is the equivalent constant-amplitude stress range, use Category C and S_{re} to characterize the fatigue strength and life of the riveted member detail.

(c) When $S_{re} \geq$ 68.9 MPa (10 ksi), use Category D and S_{re} to characterize the fatigue strength and life of the riveted member detail. For constant-amplitude loading, both S_{rm} and S_{re} are equivalent to S_r. This recommended S_r-N curve is illustrated in Figure 6-22.

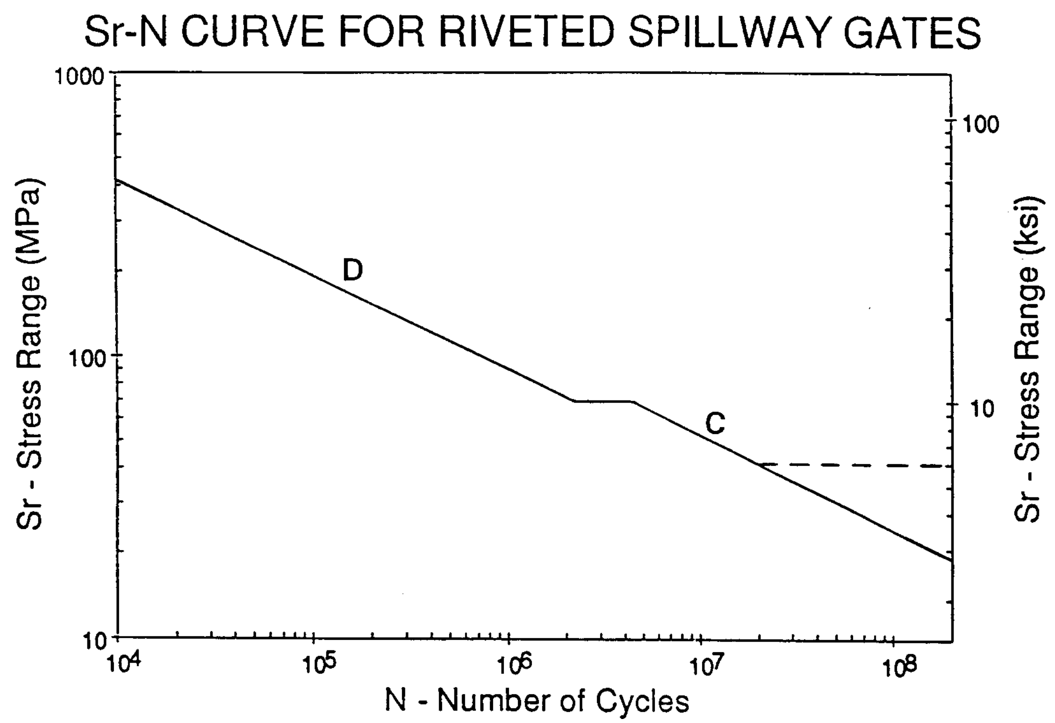


Figure 6-22. Recommended S_r-N curve for riveted gates

For severely corroded members or members with corroded, loose, or missing rivets where the clamping force is reduced or lost, lower fatigue strength curves may be more appropriate. Specifically, it is suggested that the Category E or E' curves and the corresponding fatigue limits should be used if corrosion notches are present (Chapter 2). As shown by Figure 2-5, fatigue cracks may initiate at corrosion notches instead of from rivet holes.

6-9. Evaluation of Corrosion Damage

Traditional member/frame structural analysis or even finite element methods can be used to evaluate the effect of reduction in sections from corrosion damage. To perform such an analysis, the extent of corrosion damage must be defined by reduction of appropriate section properties or thicknesses in the affected members. This should include consideration of the reduced thicknesses and change in relative proportions of the member. For example, depending on the location of the corrosion, the shear strength of a flexural member may be more affected than the flexural strength. Analysis of the complete structure incorporating the reduced sections may be warranted if the corrosion is severe and/or widespread.

6-10. Evaluation of Plastically Deformed Members

The effect of buckled or plastically deformed members can be characterized by a reduction in strength and stiffness. To assess the damage, an analysis should be performed that models the damage condition. This may simply be a frame analysis that incorporates the out-of-straightness of a crooked member or a local reduction of cross-sectional properties to model a locally buckled flange. In more significant cases of damage, a two- or three-dimensional model with the damaged locations represented as a hinge or with a damaged member being considered removed may be more appropriate.

6-11. Development of Inspection Schedules

Inspection schedules can be developed from crack length versus fatigue life curves. Figure 6-23 shows a typical crack length-fatigue life (*a-N*) curve, which can be obtained from Equation 6-8 or 6-9. Critical crack length is determined based on K_{Ic} and maximum design stress as discussed in paragraph 6-8. The time when repair is needed can be determined considering an appropriate factor of safety (2.0 is recommended), i.e., $a_r = a_{cr}/(FS)$. Remaining loading cycles before repair are then determined from a_i and a_r using an *a-N* curve as shown in Figure 6-23. Inspection intervals for a structure can be determined from the remaining fatigue life of the members (Pennsylvania Department of Transportation 1988).

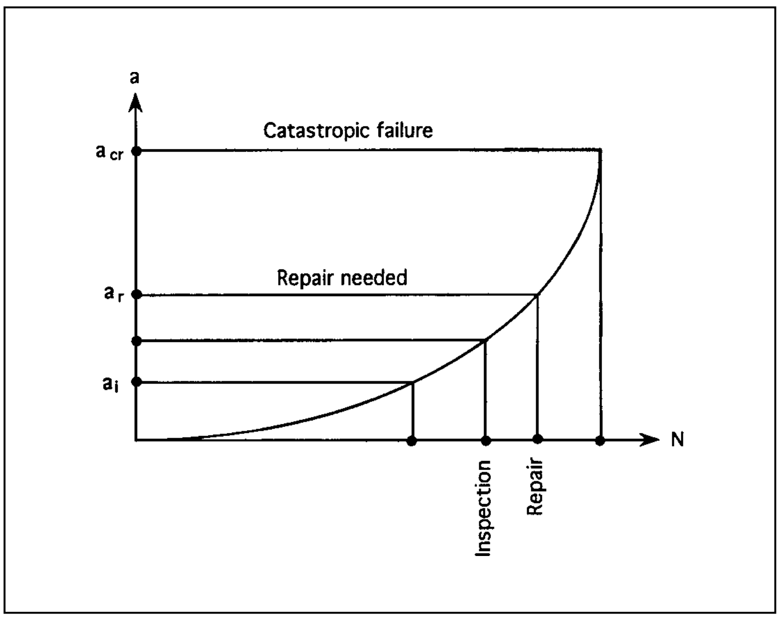


Figure 6-23. Development of maintenance schedule

6-12. Recommended Solutions for Distressed Structures

a. If a thorough evaluation of the hydraulic steel structure reveals no evidence of distress, damage, or potential failure, it should be reinspected in accordance with the inspection intervals specified in ER 1110-2-100. However, if significant deficient conditions exist (e.g., heavy corrosion, fatigue cracks, or deformations) or severe operations occur (e.g., persistent vibrations), it may be appropriate to repair and/or recommend a shorter inspection interval to ensure the structural and operational integrity of the structure. Solutions to the cracking problems can be addressed in short-term or long-term solutions. A quick solution might involve repair of fractured members using qualified welding procedures and improved fatigue details or bolted cover plates. A long-term solution would involve detailed inspection and evaluation of the critical members and connections using procedures discussed in this EM to assist in determining a more permanent solution. Repair procedures are discussed in Chapter 8, and recommended inspection intervals may be computed using fatigue principles as described in paragraph 6-11. The inspection intervals shall correspond to a crack size less than one-half of the critical crack length (i.e., employ a factor of safety equal to at least 2.0).

b. In determining the recommended action for a distressed hydraulic steel structure, the redundancy of the damaged members or connections should be considered. Obviously cracks or severe corrosion in nonredundant components should be more carefully considered. Because the conditions at each site are unique, proposing a general guideline for selecting shorter inspection intervals would be difficult. Detrimental conditions should be evaluated on a case-by-case basis using appropriate analytical tools.

c. A comprehensive maintenance and inspection program can reduce the occurrence of significant structural distress. Through a regularly scheduled cleaning and painting program, the effects of corrosion can be controlled, and by removing debris and lubricating all mechanical components, the potential overloads from lifting operations can be minimized.